Company name	Japan Atomic Power Company
Date of occurrence	18.October.2007
Unit name	Tsuruga 2
Event	Flaws Identified in the Steam Generator Reactor Coolant Inlet Nozzle Welds
International Nuclear Event Scale (INES)	0
Status of report	Final report

Status when event occurred

Considering the reported domestic and foreign events of stress corrosion cracking under the primary cooling water environment (hereafter referred to as "PWSCC") in the portion made of Ni base alloy of the reactor coolant pressure boundary of the pressurized water reactor plant, during the period of the 16th planned outage which commenced on August 26, 2007, the in-service inspection is being performed as a periodic utility inspection. Also in the 16th planned outage, a material change (from 600 series Ni base alloy into 690 series Ni base alloy having better corrosion resistivity) of the nozzles(*1) by replacing the reactor vessel upper head is being implemented.

In addition, as an action for material surface stress relieving, it is planned to perform shotpeening work (*2) for the steam generator reactor coolant inlet and outlet nozzles etc. in a sequence started with the 16th planned outage.

For the flaw which was recently reported to have been identified in the surface of the weld portion between the steam generator reactor coolant inlet nozzle (hereafter referred to as the "inlet nozzle") and the safe end(*3) in a domestic pressurized water reactor plant, it was in a location where the ultrasonic test(*4) cannot be applied because of a limitation by its configuration, and so it was discovered by an eddy current test(*5) performed as a pre-work checking activity for the shotpeening work.

Therefore, for the weld portions(*6) (a total of eight weld portions) of the inlet and outlet nozzles of four steam generators (A~D), the eddy current test of the surfaces of these nozzle weld portions was being performed since October 9, 2007 as a pre-work checking for the shotpeening work. In the course of the work, five locations with significant signal indication were identified in the inlet nozzle weld portion of the steam generator B.

*1 Nozzle: A part which is provided to connect pipe etc. to the vessel body and structurally integrated with the vessel body.

*2 Shotpeening work: A work to change tensile residual stress in a metal surface into compressive stress by striking the metal surface with metal balls at high speed.

*3 Safe end: A short pipe to connect a steam generator made of carbon steel with a pipe made of stainless steel.

*4 Ultrasonic test: A method to detect a defect in metal using ultrasonic wave. Ultrasonic wave created by a probe at the metal surface propagates inside the metal and the status of defect is identified using the aspect of wave reflection.

*5 Eddy current test: A method to detect a flaw in a test object from the change of electromagnetic induction in a material by causing the eddy current on the material surface.

*6 Weld portion: Steam generator reactor coolant inlet nozzle (carbon steel) has a weld portion between the nozzle and the safe end (a short pipe) and a weld portion between this short pipe and the reactor coolant loop pipe (stainless steel).

For the weld portion between nozzle and safe end, 600 series Ni base alloy was used as the weld metal, and stainless steel was used as the weld metal for the weld portion between the safe end and the reactor coolant loop pipe (stainless steel).

Subsequently, the eddy current test of the inlet and outlet nozzle weld portion surface was performed for the other three steam generators, and thereby significant signal indication was identified at one location for the steam generator A inlet nozzle and at 23 locations for the steam generator C inlet nozzle. These significant signal indications were all identified in the circumferential weld portion.

Further, no of significant signal indication was identified in the steam generator D inlet nozzle. Also, for the outlet nozzles, no of significant signal indication was identified for any of the (A~D) steam generators.

For all of 29 locations where significant signal indication was identified by the eddy current test, the ultrasonic test was performed, and the locations where flaw depth was possible to be clearly identified were two locations in the steam generator B inlet nozzle and seven locations in the steam generator C inlet nozzle.

Among these flaws of which depth were identified, both of the two locations of the steam generator B inlet nozzle had approx. 12 mm depth (while length were approx. 19 mm and approx. 21 mm). Considering such a flaw depth, the resultant thickness of the affected location (approx. 67 mm) was evaluated to be below 75 mm, the value described in the application document for construction permit based on the Electricity Utilities Industry Law.

Also, for the flaws in the seven locations of steam generator C inlet nozzle, the maximum depth was approx. 13 mm (length: approx. 12 mm), therefore the thickness of the affected location (approx. 65 mm) was evaluated to be below 75 mm, the value described in the application document for construction permit based on the Electricity Utilities Industry Law.

There was no impact from this event on the environment.

Summary of examination of cause

Since significant signal indication was identified in a total of 29 locations in the inlet nozzle weld portions of steam generators A, B and C, the investigation based on the causal factor analysis chart was performed.

(1) Observation by replica(*7), SUMP(*7) and etching(*9)

Among the locations identified with significant signal indication by eddy current test, one location (No.1) of the steam generator A inlet nozzle weld portion and two locations (No.1 and No.2) of the steam generator B inlet nozzle weld portion that were evaluated to have the deepest flaws in the five locations with indication were selected for the objects and the surface appearance verification by replica, the metal texture observation by SUMP and etching were performed.

*7 Replica: An indirect observation method used when a surface to be observed can not be observed directly. An organic material which has a high capability of shape following and a excellent removability is adhered to the surface to be observed, thereby a “replica” transferring the unevenness of surface is made and used to observe indirectly the surface to be observed.
*8 SUMP: Film etc. is adhered to a surface of damaged portion to transfer its shape, which is observed by a microscope. By this method, metal texture investigation for a damaged portion become possible as well as by the method using a sample cut out.
*9 Etching: A corroding process used for observation of a metal texture by optical microscope etc. In this process a test surface after polishing is corroded with oxalic acid solution etc. to remove the surface layer affected by polishing process, and the texture to be observed is exposed.

1) Steam generator A inlet nozzle weld portion
One location with significant signal indication was an association of longitudinal surface roughing (fine flaws).
Since the area having rough surface (fine flaws) is different in finished status indicating coarse finishing compared to that of the surrounding area, the rough surface was considered to be resulted from finishing by a grinder.
Further, the maximum length of surface roughing (fine flaw) was approx. 5 mm and the cracking was along the dendrite(*10) boundary indicating the branching characteristic to PWSCC.

*10 Dendrite: Column shaped crystal produced while melted metal becomes solid.

Since a trace of approx. 10 mm length thought to be that of rewelding was identified at the boundary of the inlet nozzle bevel buttering weld portion and the circumferential weld portion and the area around it was seen with coarse finishing, the affected portion was considered to be finished by a grinder after the rewelding.
The surrounding area without any rough surface (fine flaws) was seen with circumferential fine finishing, and therefore it was considered to be finished with buffing after machining by a grinder.
2) Steam generator B inlet nozzle weld portion
For the signal indications of the two locations (No.1 and No.2) investigated this time, the signal indication of No.1 consisted of two circumferential cracks of approx. 4 mm and approx. 6 mm length with an overall length of approx. 9 mm. The signal indication of No.2 was a series of multiple longitudinal cracks of approx. 1 mm to approx. 4.5 mm length with an overall length of approx. 11 mm.
Around these cracks, multiple rough surfaces (fine flaws) were distributed.
The surrounding area with rough surface (fine flaws) was seen with coarse finishing, differing from the surrounding area without any rough surface, and therefore it was considered to be finished by a grinder.
The rough surface (fine flaw) was along the dendrite boundary and the branching characteristic to the PWSCC was identified.

Since a trace of approx. 7 mm diameter thought to be that of rewelding was identified at the boundary of the inlet nozzle bevel buttering weld portion and the circumferential weld portion and the area around it was seen with coarse finishing, the affected portion was considered to be finished by a grinder after the rewelding.

The surrounding area without any rough surface (fine flaws) was seen with circumferential fine finishing, and therefore it was considered to be finished with buffing after machining by a grinder.

(2) Investigation by sampling from the actual weld portion

From the steam generator C inlet nozzle weld portion, a part including the No.3 and No.4 locations with signal indication among the 23 locations identified with significant signal indication by the eddy current test for steam generator C was taken as a boat sample and a detailed examination was performed at a hot laboratory.

1) Appearance observation

From the difference in color of the inner surface, the boundary between the safe end and the circumferential weld was identified.

Deformation and scratching were not identified for the sample taken.

2) Surface observation

Signal indication of No.3 identified by the eddy current test was of longitudinal cracking, and around this cracking, longitudinal and circumferential traces thought to be that made by grinding and buffing were identified.

Among these, the trace thought to be due to grinding was clear compared to the trace of grinding found for the inlet nozzle weld portions of steam generators A and B.

3) Penetrant test

An indication of approx. 5.5 mm in the No.3 cracking portion and an indication of approx. 4.7 mm in the No.4 cracking portion were identified.

No indications other than these were identified.

4) Fracture observation

The cracking of No.3 had a surface length of approx. 5.8 mm and the maximum depth of approx. 6.4 mm.

The cracking of No.4 had a surface length of approx. 5.8 mm, the maximum depth of approx. 3.4 mm and the crack internal maximum length of approx. 9.3 mm.

Fracture along the dendrite boundary characteristic to the PWSCC was identified for both the No.3 and No.4 cracking.

5) Fracture observation by SEM

Fracture along the dendrite boundary characteristic to the PWSCC was observed for both the No.3 and No.4 cracking.

6) Analysis of deposit on the fracture

Using an energy dispersion detector (EDS), a chemical composition analysis of the deposit on the fracture surface was performed. For both the No.3 and No.4 fracture, the main elements were the components of the weld metal (Ni, Cr, Fe etc.), and no deposit of chlorine was identified.

7) Macroscopic and microscopic observation of the cross-section

Both the cracking No.3 and No.4 were identified to be the cracking along the dendrite boundary characteristic to the PWSCC.

Further, no trace of rewelding was identified around the cracking of No.3 and No.4.

8) Hardness measurement

Hardness measurement was performed from the inner surface toward the depth direction. As a result, the near surface layer of No. 3 was of HV 321 to HV 339 and that of No.4 was of HV 309 to HV 395, thus hardening in the near surface region was verified.

This was considered to be due to the effect of machining by grinder etc.

For both the No.3 and No.4, any difference in hardness distribution along depth between the fracture and the inside was not identified.

9) Chemical composition analysis

Using an energy dispersion detector (EDS), a chemical composition analysis was performed for the inlet nozzle bevel buttering weld portion and the circumferential weld portion. As a result, the standard of 600 series Ni base alloy weld metal was met and no chlorine deposit on the surface was identified.

10) Measurement of residual stress

Residual stress in the circumferential weld portion surface was performed by X-ray residual stress measurement. The result was -591 MPa to -263 MPa in circumferential direction and -546 MPa to 244 MPa in longitudinal direction and thus the residual stress was verified to be compressive.

11) SMP observation

Near cracking No.3, four locations having fine cracking of approx. 240 μm to 4.5 mm were identified.

The amount of surface roughing (fine flaws) was less than that found for the inlet nozzle weld portion of steam generators A and B.

Further, as far as the area where the SUMP observation was performed, no rewelding trace was identified.

12) Additionally performed microscopic cross-section observation

For the fine cracking found in the four locations near No.3 cracking, microscopic cross-sectional observation was performed. Among the multiple fine cracking, the deepest one was of 0.8 mm depth and it was identified to be a cracking along the dendrite boundary.

Further, no cracking having a depth greater than No.3 cracking was identified.

(3) Investigation of manufacturing and operation history

1) Investigation of manufacturing history

Steam generators of Tsuruga 2 were manufactured during the period of July 1982 to April 1985, and installed at the site during February to July 1985. The work records and inspection records for that period were confirmed and a hearing from relevant persons was performed to investigate the manufacturing history.

As a result, no singularity in the manufacturing procedure of the inlet nozzle was identified, the welder had enough experiences, and no record of rewelding performed was identified from the records investigated this time.

Further, as a result of hearing from relevant persons, the type of tools used for grinding and buffing of the circumferential weld portion was confirmed to be possible to differ by the worker.

2) Investigation of operational history

Operational history of Tsuruga 2 from the start of operation (February 17, 1987) to the start of 16th planned outage was investigated and the result was as follows:

a. Reactor coolant temperature and pressure

Tsuruga 2 has experienced since the start of operation one event of reactor automatic shutdown, six events of manual shutdown, and three events of power suppression. None of the events accompanied with transients other than these were identified.

Further, it was confirmed that during these transients, abnormal temperature and pressure was not indicated.

b. Status of water chemistry control

Since the start of Tsuruga 2 operation, the water chemistry of reactor coolant has been kept to satisfy the values defined by plant's safety preservation rules and no harmful material such as chlorine etc. was identified.

(4) Confirmatory test for surface machining condition (Mockup test)

After welding the inlet nozzle to the safe end, finishing of the inner and outer surfaces with grinding and buffing was performed, and this could be a cause of hardening and high tensile residual stress. Further, in the area where finishing with a grinder was performed for the actual weld portion, cracking and rough surface (fine flaws) were identified. Considering these, a mockup test to simulate the surface finishing condition of the actual weld portion was performed.

For testing, buildup welding by 600 series Ni base alloy was performed on a stainless steel plate, then it was finished with a grinder and a buff under the finishing condition based on the result of hearing, and using this as the test sample, surface condition observation, residual stress measurement, hardness measurement and roughness measurement were performed.

1) Surface condition observation

From the samples (a total of ten species) made with variation of surface finishing condition by grinder and buff, the surface replicas were taken and compared with that taken from the actual weld portions. The result was as follows:

a. For the replica taken from steam generator A inlet nozzle weld portion, the area of grinder machining with rough surface (fine flaws) was similar to the finished status by air grinder (skill touch) of the test sample No.6.

Also, it's surrounding area finished by buffing and having no cracking was in the same condition as the condition of sample No.4 finished by buffing after air grinder treatment (skill touch).

b. For the replica taken from the steam generator B nozzle weld portion, the area machined by grinder and having the cracking of No.1 and No.2 and the rough surface (fine flaws) around them was in a same condition as the condition of the sample No.6 finished by air grinder (skill touch).

Also, it's surrounding area finished by buffing and having no cracking was in the same condition as the condition of the sample No.4 finished by buffing after air grinder treatment (skill touch).

c. For the replica of the boat sample taken from the steam generator C nozzle weld portion, general finishing condition of the sample remained a wide clear trace of grinder finishing in the surface finished by buffing, and in a same condition as the sample No.9 finished by buffing after high frequency grinder finishing.

2) Residual stress measurement

a. For the surface (of the sample No.6) finished by air grinder (skill touch), residual stress was measured and the result was 470 MPa as an average.

b. For the condition finished by buffing after air grinder finishing (sample No.4), residual stress was measured and the result was -292.5 MPa as an average.

c. For the condition finished by buffing after high frequency grinder finishing (sample No.9), residual stress was measured and the result was -211 MPa as an average which was a compressive stress as the actual weld portion.

d. For the condition finished by buffing after high frequency grinder finishing (sample No.9), a local residual stress was measured within a small area around the bottom of grinding groove, and thereby a tensile stress was verified to exist.

Since there was a difference in residual stress by approx. 680 MPa between the surface finished by high frequency grinder and the surface additionally finished by buffing, the residual stress at the bottom of grinding groove in the area with deep groove made by high frequency grinder was considered possible to be estimated by adding a correction by approx. 680 MPa to the value obtained from a general residual stress measurement.

3) Hardness measurement

For the area finished by buffing after finishing by high frequency grinder, the hardness in near surface layer was HV 283 to HV 384. By this result, as well as by the result of hardness measurement by sample from actual weld, the hardening in the nearby surface layer was verified.

(5) Review of literature

Literature on cracking in 600 series Ni base alloy weld was reviewed. As the events of damage in a similar portion, an event of leakage from the reactor vessel outlet nozzle weld at V.C. summer in the US (discovered in October 2000) and an event with ultrasonic test indication identified for the reactor vessel outlet nozzle weld of Ringhals 3 and 4 in Sweden (discovered in August and September 2000) were reported.

Also, in Tsuruga 2, an event of cracking in the nozzle for pressurizer relief valve etc. occurred (discovered in September 2003).

Cracking in all of these cases was longitudinal cracking, and cracking in the case of V.C. Summer in US and Tsuruga 2 developed in the weld metal stopped at the boundary with low alloy steel and at the boundary with the safe end. The cause of cracking in both cases is considered to be PWSCC occurred due to high tensile residual stress resulted from repair welding.

Further, on PWSCC caused in 600 series Ni base alloy weld, the 360°C temperature accelerated SCC constant load test was performed and from it PWSCC is considered to be caused at a stress greater than 300 MPa.

(6) Other forms of damage

Also investigation for the possibility of ductile cracking and fatigue cracking was performed. Though, there was no anomaly in usage environment condition and material used and thus these were not considered as the cause. In addition, for cracking due to high temperature during manufacturing, what could be a cause was not identified from the manufacturing history and inspection records.

(7) Summary of the investigation result

The rough surface (fine flaws) and cracking identified in the inlet nozzle weld portion of steam generator A, B and C were all along the dendrite boundary and they were verified to exhibit PWSCC aspects.

Further, for the residual stress (circumferential) in surface layer due to finishing by grinder etc in the steam generator C inlet nozzle weld portion, it was confirmed that summing the residual stress measured value for the actual weld portion boat sample measured at the hot laboratory (-591 MPa to -263 MPa) and the correction value determined from the result of the mockup test (approx. 680 MPa), the surface residual stress at the bottom of groove made by grinder was evaluated at approx. 90 MPa to approx. 420 MPa, and thus a tensile stress exceeding the PWSCC occurrence condition of approx. 300 MPa could exist.

Further, the residual stress in surface layer due to air grinder finishing (skill touch) in the area where cracking and rough surface (fine flaws) were identified in the inlet nozzle weld portion of steam generators A and B was verified to be equivalent with the stress in the bottom of groove made by high frequency grinder from the result of the mockup test, therefore it was also considered to be equivalent with the surface stress of cracking in steam generator C inlet nozzle weld portion during operation.

The operational stress (mainly due to internal pressure) caused inside the pipe material was larger in the circumferential direction than in longitudinal direction and this was considered to be the reason that the direction of cracking development was longitudinal.

From the above, these cracking and rough surface (fine flaws) was considered to be due to PWSCC.

Cause of event

During manufacturing of steam generator, the inlet nozzle was welded to the safe end using 600 series Ni base alloy weld metal and finishing by air grinder and buff was performed. For the area (steam generator A and B SUMP investigation area) where finishing by air grinder (skill touch) was performed after rewelding and the area (steam generator C boat sample investigation area) where the trace of finishing by high frequency grinder remained locally, high residual stress in surface layer of the inner surface was caused. PWSCC was considered to have occurred due to this high stress and developed in longitudinal direction due to operational stress etc.

Measures to prevent recurrence

For steam generators B and C, the following recurrence prevention measures will be implemented:

(1) The circumferential weld portion inner surface will be machined for entire circumference in order to remove shallow cracking, and then deeper cracking will be removed by grinder.

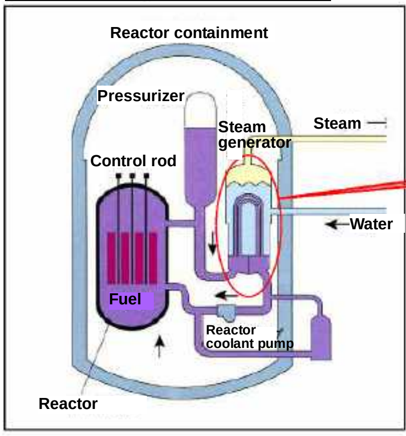
(2) Subsequently, for the area where deeper cracking was removed, buildup welding with 600 series Ni base alloy will be performed. Then, on the circumferential weld portion inner surface entire circumference machined to remove shallow cracking, buildup welding will be performed using 690 series Ni base alloy which has a better corrosion resistivity.

(3) For the sake of caution, from the view point of reducing residual stress in the area where buildup welding was performed with 690 series Ni base alloy, buff finishing will be performed for the area.
Also, for steam generator A of which circumferential weld portion was identified to have rough surface (fine flaws), removal of the rough surface will be performed based on considerations for the structural strength of the portion, the function of stainless lining material (inner surface buildup portion) of the inlet nozzle inner surface and its inspectability for the eddy current test from the inner surface side.
Then, the residual stress in the weld portion surface will be reduced by shotpeening etc.

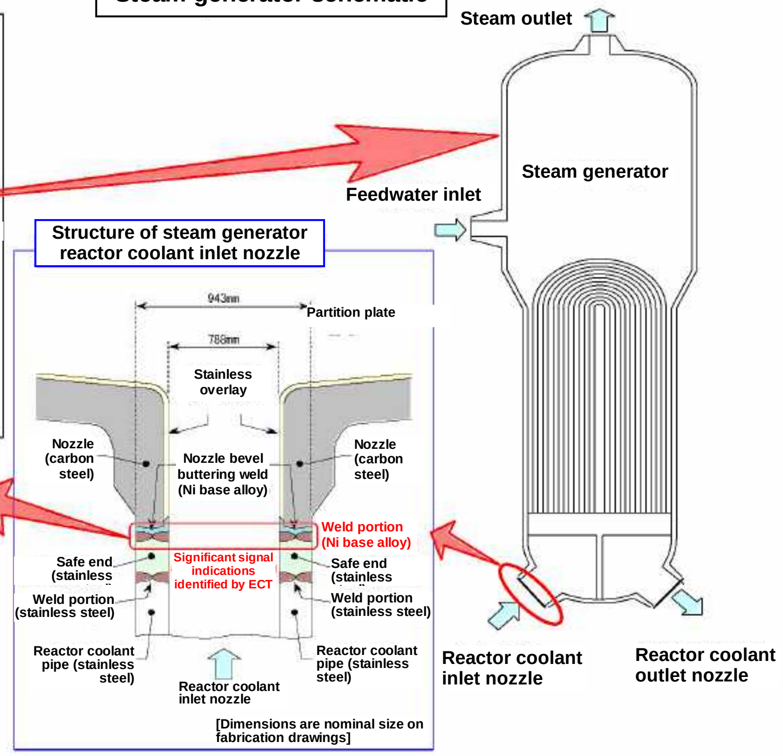
Attachment (1/4)

Periodic inspection status at Tsuruga Unit 2
(The cause and countermeasures of the flaws in the steam generator reactor coolant inlet nozzle welds)

Location of occurrence

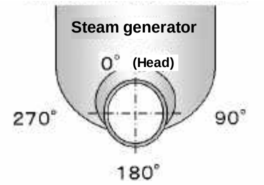


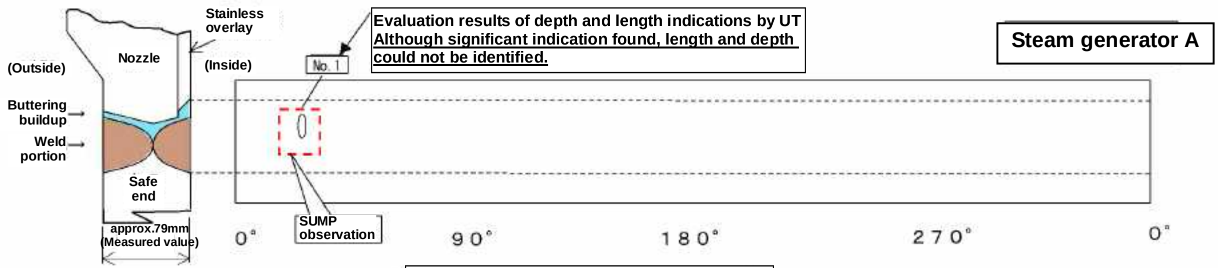
Steam generator schematic

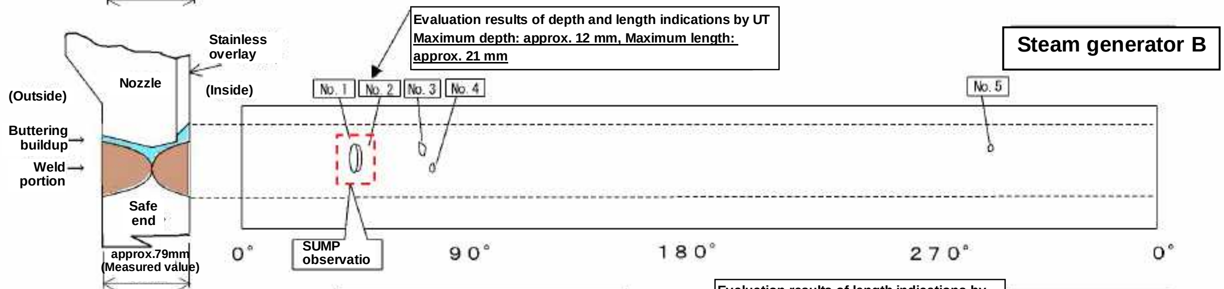


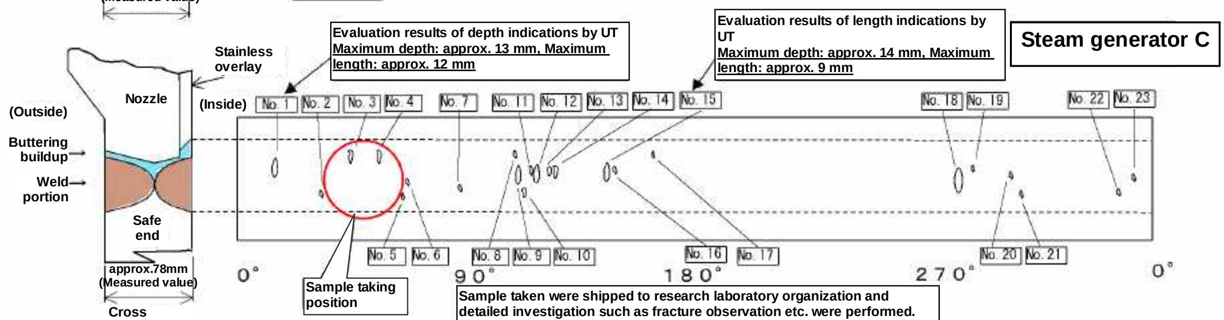
ECT results (location with significant indication)

View from steam generator side









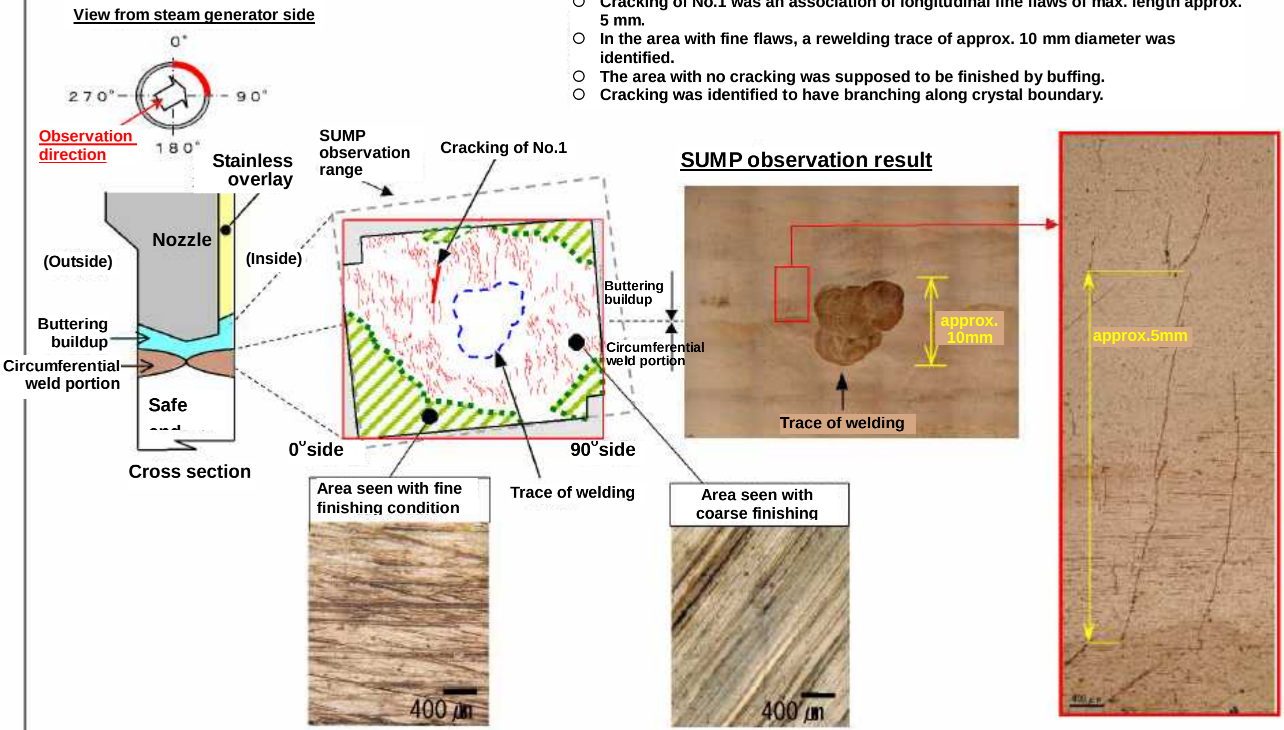
(Value in the application for construction plan approval: approx.75mm)

Attachment (2/4)

Cause investigation result

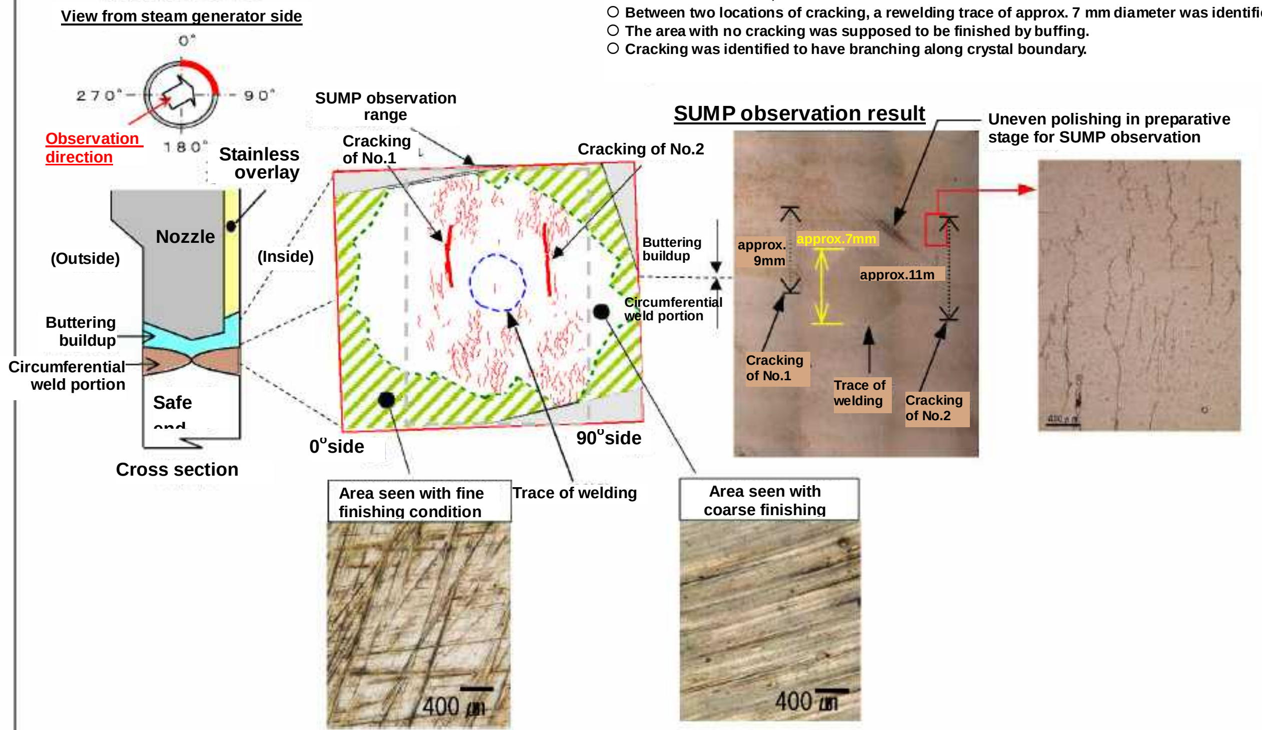
Steam generator A cracking of No.1

- Cracking of No.1 was an association of longitudinal fine flaws of max. length approx. 5 mm.
- In the area with fine flaws, a rewelding trace of approx. 10 mm diameter was identified.
- The area with no cracking was supposed to be finished by buffing.
- Cracking was identified to have branching along crystal boundary.

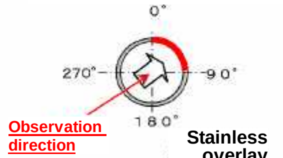


Steam generator B cracking of No.1 and No.2

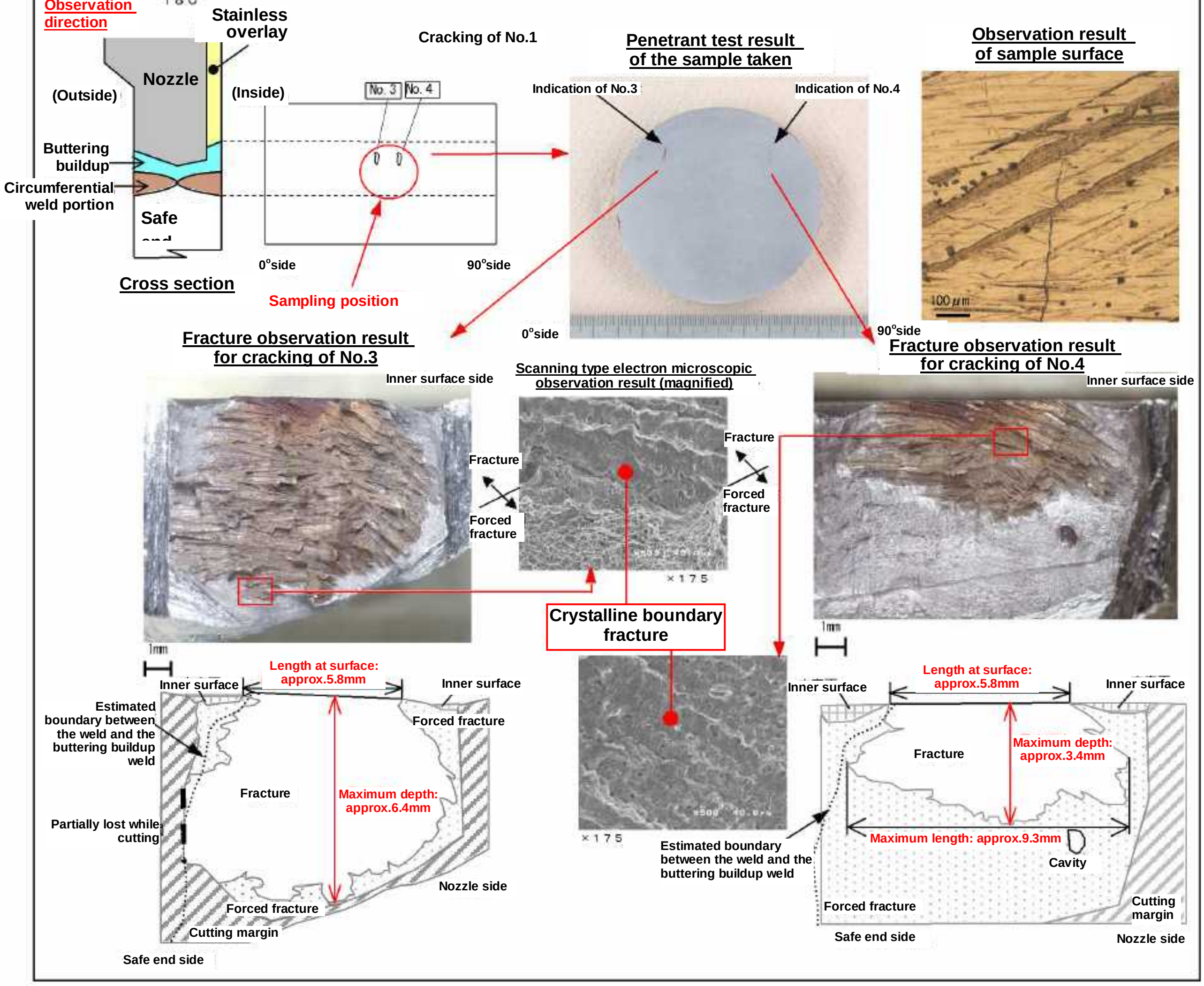
- Cracks of two locations were longitudinal with length of approx. 9 mm and approx. 11 mm.
- Around these cracks, fine flaws were identified.
- Between two locations of cracking, a rewelding trace of approx. 7 mm diameter was identified.
- The area with no cracking was supposed to be finished by buffing.
- Cracking was identified to have branching along crystal boundary.



Steam generator C cracking of No.3 and No.4



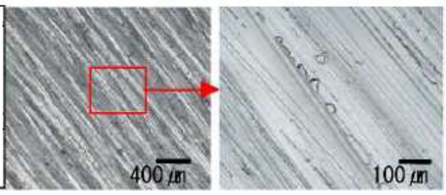
- By penetrant test, cracking of No.3 and No.4 were identified with indication of approx. 5.5 mm and approx. 4.7 mm, respectively.
- Linear pattern was seen all over the sample surface and the pattern was more clear than that seen for steam generator A and B.
- By fracture observation, maximum depth was identified to be approx. 6.4 mm (No. 3) and approx. 3.4 mm (No.4).
- Fracture branching along weld metal crystal grain boundary was identified.



Confirmatory test for surface machining condition

Condition around cracking of steam generator A and B was simulated.

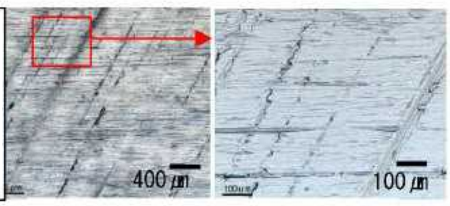
(Finished by grinder-buff-grinder sequence)



Approx. 470 MPa as average (Tensile stress)

Condition around cracking of steam generator C was simulated.

(After coarser grinding process, finished by buffing)

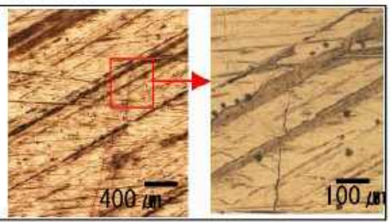


Approx. 210 MPa as average (Compressive stress)

Evaluation by confirmatory test for surface machining condition

- Approx. 680 MPa difference exist between the surface processed by grinder and the surface additionally finished by buffing.
- In area of deeper grinding groove, residual stress at groove bottom is considered possible to be estimated by adding a correction of approx. 680 MPa to a general measured value.
- Adding 680 MPa to residual stress measured value for the sample taken from steam generator C, residual stress at grinding groove bottom was estimated at 90~420 MPa tensile.

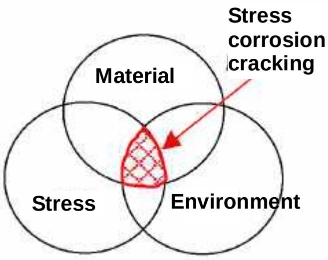
Residual stress measurement result for the sample taken from steam generator C (for reference)



263~591 MPa (Compressive stress)

Presumed cause

From the characteristics of fracture etc. the cause is presumed to be stress corrosion cracking occurred and developed by coincidence of the three factors below.

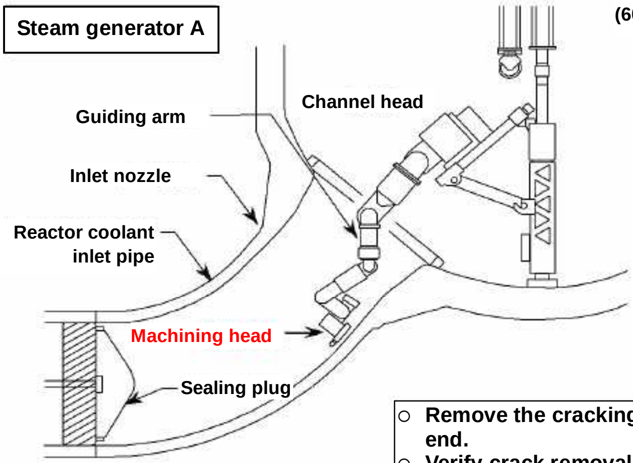


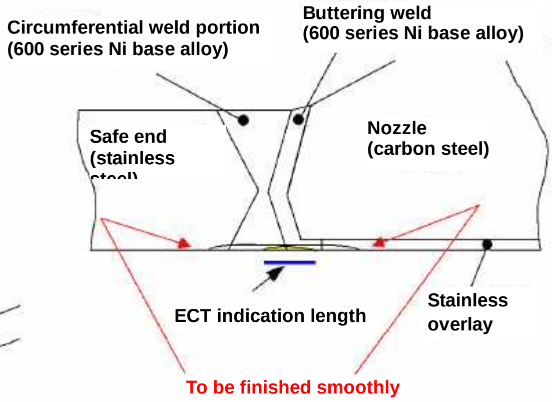
Environment	○ Verification test of temperature effect on stress corrosion cracking occurrence [Operated in primary water environment including high temperature, high pressure etc.]
Material	○ Stress corrosion cracking occurrence test in high temperature water for 600 series Ni base alloy [600 series Ni base alloy of which stress corrosion cracking has been verified is used as the weld metal.]
Stress	○ Evaluation by surface machining condition verification test [Due to welding and grinding after it during steam generator manufacturing, high tensile residual stress was caused in surface layer of nozzle inner surface.]

Material, environ and stress are all in the region of stress corrosion cracking.

Countermeasures

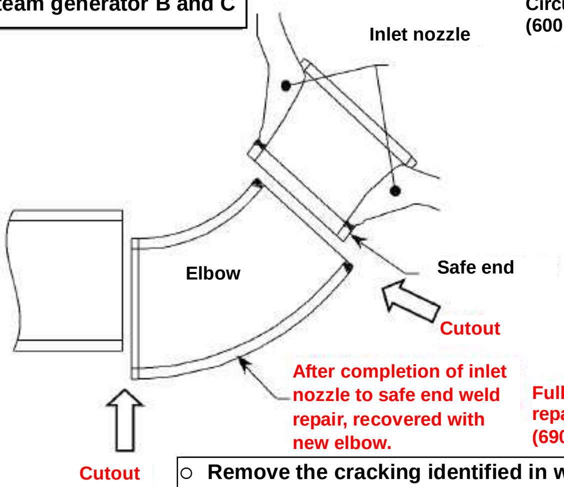
Steam generator A

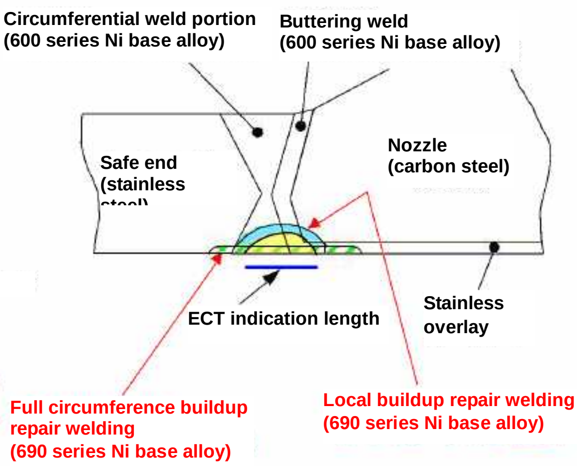




- ○ Remove the cracking identified in weld between inlet nozzle and safe end.
- ○ Verify crack removal by eddy current test (ETC)
- ○ Considering future inspectability, finish inner surface smoothly.
- ○ Perform shotpeening to reduce residual stress in weld portion surface.

Steam generator B and C





- ○ Remove the cracking identified in weld between inlet nozzle and safe end.
- ○ For the position locally machined, perform buildup welding using 600 series Ni base alloy.
- ○ Perform full circumferential surface buildup welding using 690 series Ni base alloy which has better corrosion resistivity.

In performing strength evaluation required for construction plan application, evaluation of calculation condition for safe end thickness (75 mm) etc. to be performed according to current evaluation method.